Mechanical and thermal properties, and comparative life-cycle impacts, of stabilised earth building products

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Abstract:

The study presented here investigates the use of alkali-activation and waste materials in stabilised compressed earth construction products. Experimental results for mechanical and thermal properties are presented. Environmental impacts are also compared in a Life Cycle Assessment together with a wider discussion of construction practicalities. Construction and demolition waste shows potential as an aggregate, with processed ground blast furnace slag, together with fly ash, particularly promising for alkali-activated stabilisation. Thermal conductivities of materials using the processed ground blast furnace slag were noticeably lower. Alkali-activated compressed earth blocks appear most promising for reducing the global warming potential of stabilised earth construction.

Keywords:

Alkali-activation; Compressed earth blocks; Compressive strength; Masonry; Life Cycle Analysis; Rammed earth; Stabilised earth construction; Thermal properties; Waste materials.

1. Introduction

Stabilised earth construction, including compressed earth masonry units and rammed earth, are now relatively well established as contemporary building materials and techniques in a number of countries, including India, Australia and South Africa. This development has been supported by research on cement stabilised earth materials over the past 50 years [1, 2], and construction is now widely supported by national standards and codes of practice [3, 4, 5]. The area around Bengaluru, South India, in particular, supported by research and development, has seen many thousands of buildings successfully completed using stabilised compressed earth blocks.

Though alternatives, such as lime and bitumen, have been trialled, Portland cement remains by far the most commonly used stabiliser in earth construction [6]. Like concrete, the hydrated cement gel binds together the aggregates in earthen materials to form a material that is more water resistant and generally has higher strength. Densification, through compaction, further improves strength and durability. In recent years growing concerns about the environmental impacts of cement manufacture, in particular the associated carbon dioxide emissions, have led researchers to again explore alternative binders for concrete and stabilised earth materials. One such alternative approach is alkali-activated binders, also known as geopolymers. Alkali-activated materials are produced by a reaction of aluminosilicates under alkaline conditions. The reaction makes a hardened amorphous binder of hydrous alkali-aluminosilicates and/or alkali-alkali earth-aluminosilicates [7]. Strength development of the alkali-activated materials most commonly relies on curing at temperatures around 50-80^{o}C for a few days. The attraction of alkali-activated materials is the opportunity to reduce carbon dioxide emissions, compared to cement and lime, during manufacture.

Muñoz et al. [8] produced alkali-activated stabilised materials from clay soils combined with alkali-activators. The binders combined Sodium Hydroxide (NaOH) with Sodium Silicate (Na_2SiO_2), and following a curing at 65 °C for 7 days stabilised earth materials with a compressive strengths up to 7.6 N/mm^2 were successfully produced. Elert et al. [9] reported on alkali-activated solutions to consolidate adobe test blocks. Combining a 5M NaOH with 5M Potassium Hydroxide (KOH), test results showed significant improvement in both water resistance and mechanical strength. Fly ash has also been successfully used as a precursor for the production of alkali-activated compressed earth blocks [10]. Blocks with compressive strengths up to 12 N/mm^2 were produced using up to 15% fly ash with 13.7% alkali-activator.

Miranda et al. [11] produced alkali-activated compressed earth blocks suitable for low rise load bearing masonry applications using soils with construction and demolition waste materials. Meanwhile Sore et al. [12] produced blocks having at least 4 N/mm^2 compressive strength from a 10-15% alkali-activator binder content (using NaOH and Metakaolin). The alkali-activated blocks had lower thermal conductivities (around 0.7 W/mK) than the denser cement stabilised blocks (around 1.2 W/mK).

In 2018 Dahmen et al. [13] compared the LCA of cement stabilised and alkali-activated stabilised blocks with conventional concrete blocks. They reported that the embodied carbon contents of the cement stabilised and alkali-activated blocks were similar, but around 45% less than similar concrete blocks. In their LCA Dahmen et al. [13] expressed concerns about existing production methods for the alkali-activated blocks, with highest impacts reported for human health, ecosystems, water and resource usage. In 2018 Marsh et al. [14] developed alkali-activated stabilised earthen materials using clay soil alumino-silicates as the precursors.

Stabilised earth construction materials are most effective with sandier soils having relatively low clay contents. Therefore, it is common practice for higher clay bearing natural sub-soils to be blended with finer aggregates, such as building sand and aggregates, to develop a grading more suited to stabilisation. In many countries sourcing natural high quality aggregates is a problem due to diminishing supplies and associated environmental impacts. In Southern India, for example, the use of crushed quarried granite has produced an alternative source for fine (building sand) aggregates. Other alternative aggregates include the potential use of recycled materials and construction and demolition wastes. A 1:1 mixture of soil and concrete demolition waste, with 10% cement stabilisation, produced rammed earth of sufficient compressive strength [15]. However, in 2018 Arrigoni et al. [16] reported that mixing recycled concrete aggregates with cement stabilised rammed earth raw materials led to a reduction in compressive strength.

This paper reports on a collaborative study between India and UK developing alkali-activated compressed earth blocks and rammed earth, and also exploring opportunities for use of aggregates from construction and demolition waste blended with natural soils. Test results for mechanical strength, compressive stress-strain properties, and thermal properties of alkali-activated and cement stabilised prototype products are reported, together with findings from a preliminary Life Cycle Analysis comparing impacts. The aim of the study presented here has been to explore the potential for using alkali-activated binders as alternatives to cement for stabilised earth construction materials, and assess the wider use of solid waste materials. The specific objectives to meet this aim were:

- Compare mechanical and thermal performance of cement stabilised and alkali-activated stabilised compressed earth blocks, compressed earth block masonry, and rammed earth;
- Assess potential to incorporate solid inorganic wastes (construction and demolition waste; processed granulated blast furnace slag) into compressed earth blocks and rammed earth materials;
- Compare life-cycle impacts of cement and alkali-activated stabilised earth construction products.

The work is expected to support the further development of affordable stabilised earth construction in both developed and developing countries.

2. Materials and mix proportions

2.1 Soils and aggregates

A residual natural soil, sourced from a site near Bengaluru, Karnataka, India, was chosen as the base material for compressed earth block and rammed earth construction. The grading curve of the soil is presented in Figure 1, with further properties summarised in Table 1 below. The clay fraction mineralogy is kaolin based.

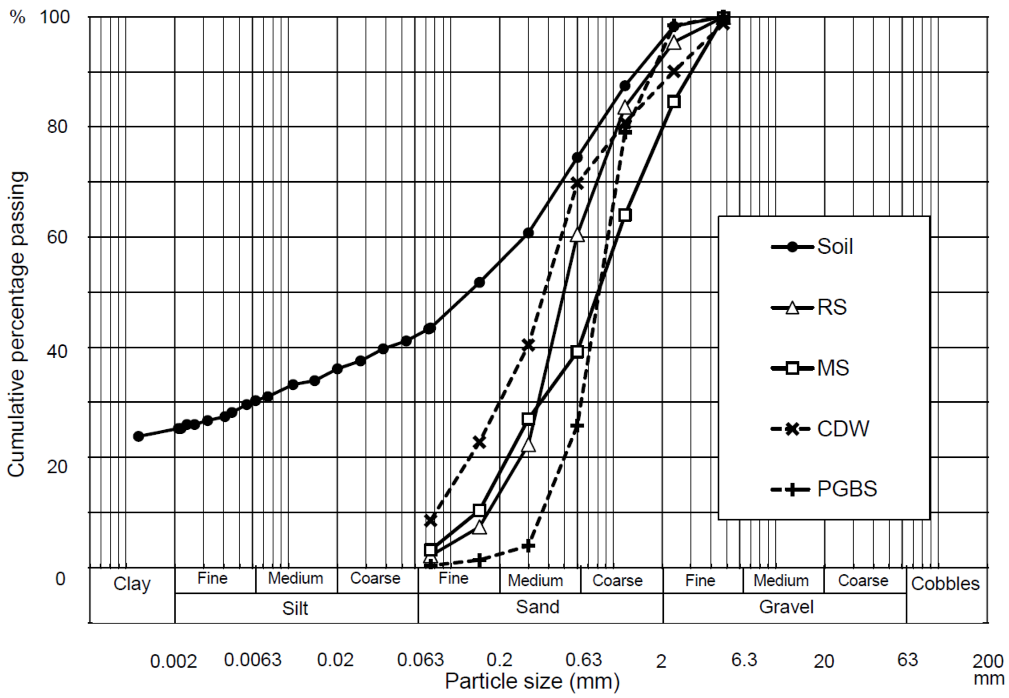


Figure 1. Particle Size Distribution curves for aggregates

Table 1. Soil properties

Property	
PSD summary	
Clay content	25%
Silt content	17%
Sand content	55%
Gravel content	3%
Atterberg limits	
Shrinkage limit	18.7%
Plastic limit	20.2%
Liquid limit	34.4%

A variety of aggregates [Manufactured Sand (MS); Construction and Demolition Waste (CDW); Processed Granulated Blast-furnace Slag (PGBS)] were blended with the natural soil to improve their suitability for compressed earth block and rammed earth construction. The MS is produced by crushing granite rock quarried locally to

Bengaluru; it has become an established alternative to natural river sands for a wide variety of building uses including concretes and mortars. The grading curves for a River Sand (RS), used for capping specimens, and MS, are also presented in Figure 1. The MS was also used as the fine aggregate for cement-lime mortars in a series of masonry prism tests.

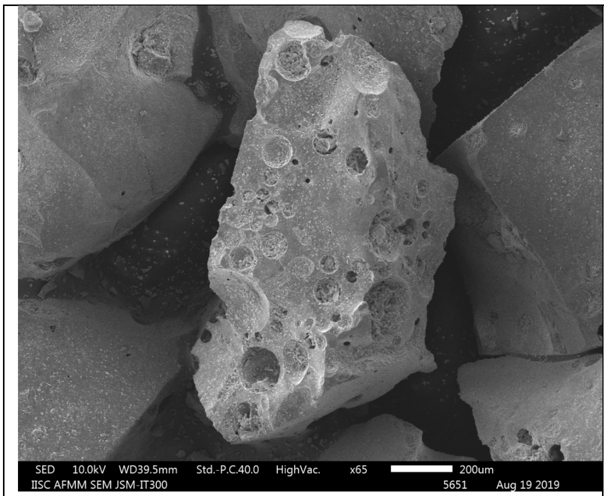
Two solid waste materials were selected for use in this study: CDW, and PGBS. The CDW was sourced from a supplier in Gujarat, India. The graded waste material is a residue from crushing and recycling concrete, and other building demolition waste, including ceramic bricks and mortars, following extraction of larger aggregates for reuse in concrete. The grading curve for the CDW is also presented in Figure 1.

The PGBS was sourced from the JSW steel plant, Toranagallu, Bellary district, Karnataka, India. PGBS is a granulated aggregate material sourced from cooling molten ash in steel production process. The grading curve for the PGBS is also presented in Figure 1. The chemical compositions of the PGBS, Fly Ash (FA) and CDW, determined by SEM/EDX, are presented in Table 2.

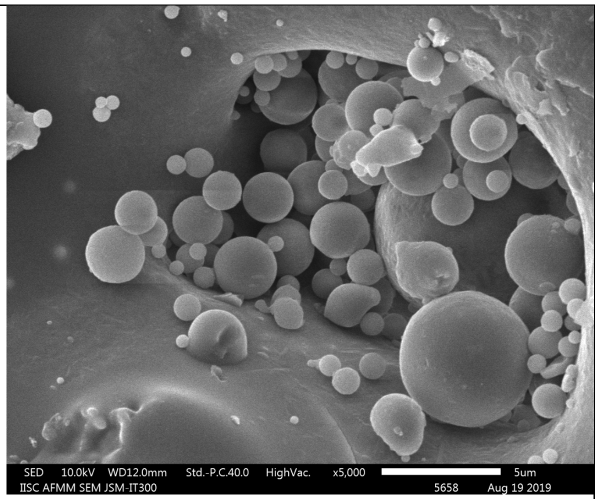
Table 2. Chemical composition of PGBS, FA and CDW

Element	PGBS	FA	CDW
O	48.7%	42.0%	38.0%
Si	15.9%	26.8%	38.3%
Al	11.6%	20.8%	10.5%
Ca	17.9%	1.3%	5.1%
Mg	3.6%	-	-
K	0.8%	2.1%	1.6%
Fe	0.7%	5.1%	3.2%
Na	-	-	3.1%
Mn	0.8%	-	-
Ti	-	1.9%	-
Co	-	-	0.2%

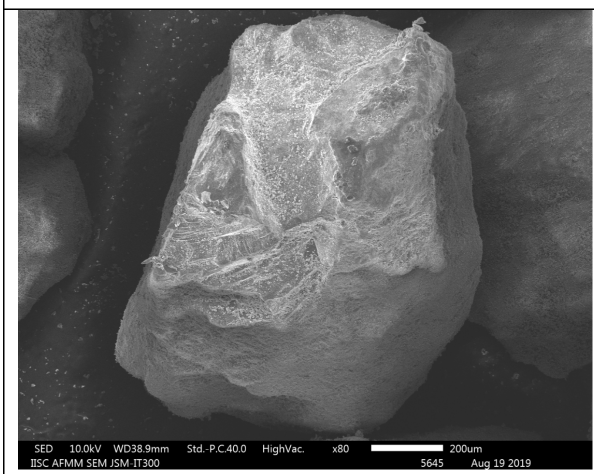
The SEM images for the PGBS, FA, CDW and MS aggregate are reproduced in Figure 2. The individual particle sizes, and grading (Figure 1), for the PGBS, CDW and MS are similar, whilst the typically much finer particle size of the FA is also evident in Figure 2(ii). The CDW and MS show similar irregular particle shapes typical for crushed materials, whilst the higher surface porosity of the PGBS particles can be seen in Figure 2(i).



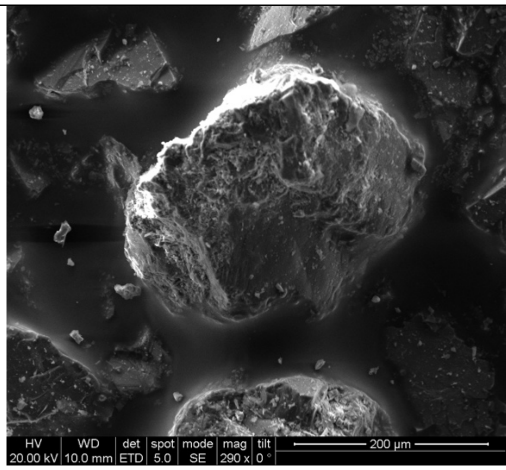
(i) PGBS



(ii) FA



(iii) CDW



(iv) MS

Figure 2. SEM images for PGBS, FA, CDW and MS

2.2 Cement, lime, precursors, and alkali activators

The study used a Portland Cement, Grade 53, [17]. Hydrated lime [18] was used together with the PC to stabilise the rammed earth and compressed earth blocks, and was also used in the masonry mortars. FA from the Raichur Thermal Power plant, Karnataka, India, was used as a precursor for the alkali-activation process. The chemical composition of the FA is given in Table 2. Sodium Hydroxide (NaOH) was used as the alkali-activator. The NaOH pellets were diluted in water, and used in 12M concentrations throughout together with the FA.

The pozzolanicity of the MS, CDW, PGBS, MS and FA were measured by conducting lime reactivity tests in accordance with Indian Standard 1727 (1967) [19]. The pozzolanic action of each material, reported in Table 3, is represented by the compressive strength of 50 mm cubes; higher compressive strength shows greater pozzolanic reactivity with hydrated lime. As expected the MS shows no pozzoloanic reactivity, whilst the CDW and PGBS show similar, but low, pozzolanicity, with the FA showing greatest reactivity with lime.

Table 3 Pozzolanicity (lime reactivity) of materials

Material	Compressive strength (N/mm^2)
MS	Nil
CDW	0.25
PGBS	0.27
FA	2.99

The water absorption of the fine aggregates used in the study were also determined in accordance with ASTM C128-15 [20] and are reported in Table 4. The CDW shows highest water absorption of the three aggregate materials.

Table 4. Water absorption of aggregate materials

Aggregate	Water absorption, %
MS	0.38
PGBS	1.23
CDW	3.57

2.3 Mix proportions

In the series of compressed earth blocks and rammed earth tests the following binder mix proportions (by mass) were used:

- 7% cement + 2% Lime
- NaOH [12M] + 15% Fly ash

The mix proportions were determined from an earlier study by the authors, in which mechanical properties of materials were determined from tests on small prototype cylinders [21]. The aggregates used with these two binder combinations for the rammed earth and compressed earth blocks were as follows:

- 1:1 by mass [Soil : Construction and Demolition Waste (CDW)]
- 1:1 by mass [Soil : Manufactured Sand (MS)]
- 1:1 by mass [Soil : Processed Granulated Blast furnace Slag (PGBS)]

The moisture contents at compaction for the rammed earth cylinders and compressed earth blocks, for all three aggregates, were controlled consistently at 10%.

A 1:1:6 (cement: lime: sand) by volume mortar mix was chosen for a series of compressed earth block masonry prism tests. The PC and hydrated lime binders were used together with the MS (Figure 1). Mortar cubes were cast for subsequent compressive strength characterisation tests.

3.0 Research Methodology

3.1 Programme

The experimental research programme comprised mechanical property tests on full-size prototype compressed earth blocks, prototype rammed earth cylinders and masonry prisms. In addition, basic thermal property tests were also completed on both the blocks and rammed earth specimens. A comparative Life Cycle Analysis was also completed to compare the environmental impacts of the cement and alkali-activated materials. The research programme was a collaboration between the Indian Institute of Science, India, and the University of Bath, UK, using test facilities at both institutions. All materials were sourced, and all specimens were manufactured, in India.

3.2 Specimen manufacture

3.2.1 Rammed earth cylinders

The rammed earth cylinders were prepared by manually compacting the freshly prepared materials in a 200 mm high and 100 mm diameter steel moulds. The materials were initially mixed in a rotating drum concrete mixer. The rammed earth was compacted in three equal layers, Figure 3. For the compaction process the fresh mix was carefully batched by mass, equally for each layer, to achieve a target dry density of 1800 kg/m^3. Following compaction the 36 cement stabilised cylinders were moist cured under damp burlap for 28 days. In contrast the 36 geopolymer stabilised cylinders were heat cured at 80 ^{o}C for 3 days (72 hours) after compaction. The chosen target density and 10% moisture content at compaction was based largely on past experience with the materials [22,23].

Figure 3. Rammed earth cylinder and compressed earth block

3.2.2 Compressed earth blocks

The compressed earth blocks, measuring 230 x 110 x 70 mm nominally, were manufactured in a manual constant volume type block press; such presses are commonly used in India, and around the world. The freshly prepared loose materials, mixed in a concrete pan mixer, were carefully weighed and placed into the mould to achieve a target dry density of 1800 kg/m^3. The dry materials were mixed together first, and then the fluid (water or alkaline activator solution) added afterwards to achieve the desired moisture content: 10% water for the cement blocks and 10%

solution for the geopolymer blocks. For compaction the mould lid is closed and the ram raised by lowering the lever arm. Thereafter, the lid is retracted and the freshly compacted block extruded from the mould by once again lowering the lever arm. The blocks had a small double frog indented during compaction, Figure 3.

Following compaction the cement stabilised blocks were moist cured under damp burlap for 28 days. The geopolymer stabilised blocks were heat cured at 80 ^{o}C for 3 days (72 hours) following compaction. Around 30 blocks were produced for each mix. The dry density reported for the blocks has been based on net volume of each unit.

3.2.3 Compressed earth block masonry prisms

To measure the mechanical properties (compressive strength and elastic modulus) of masonry produced using the compressed earth blocks, a series of small stack bonded prism tests were completed. The four brick high prisms, Figure 4, were built after the cement blocks had reached 28 days, or the alkali-activated blocks had been heat cured for 3 days (72 hours) and air dried in the laboratory for about 28 days, and tested once the mortar had achieved a further 28 days age from prism construction. A 1:1:6 (cement : lime : manufactured sand, by volume) mortar was considered appropriate for the block strengths achieved. The blocks were laid with a 10 mm mortar joint. The prisms were capped top and bottom with a 1:3 cement : river sand mortar and cured, wrapped in burlap, for the 28 days prior to testing. The average 28 day wet compressive strength of the 1:1:6 cement lime mortar was 5.3 N/mm^2.

Figure 4. Compressed earth block masonry prism

3.3 Compression tests

The rammed earth cylinders were tested saturated following 48 hours immersion in water. Some rammed earth cylinders were instrumented with 100 mm long extensometers to measure axial strain during compression loading, Figure 5. Compressive loading was applied to the rammed earth cylinders at a rate of 6 μm/sec in displacement controlled mode. The alkali-activated specimens were initially heat cured for 3 days (72 hours) and then air dried in the laboratory for a minimum of 28 days before testing. The cement & lime specimens were moist cured for 28 days curing before testing or storage for later testing (series 2). The compressive strength tests were conducted in two phases: series 1 were tested at the Indian Institute of Science, India; series 2 were tested between 200 and 230 days after compaction at the University of Bath, UK. The second series had been transported to the UK for thermal testing (see below). In both series three rammed earth cylinders were tested in each category.

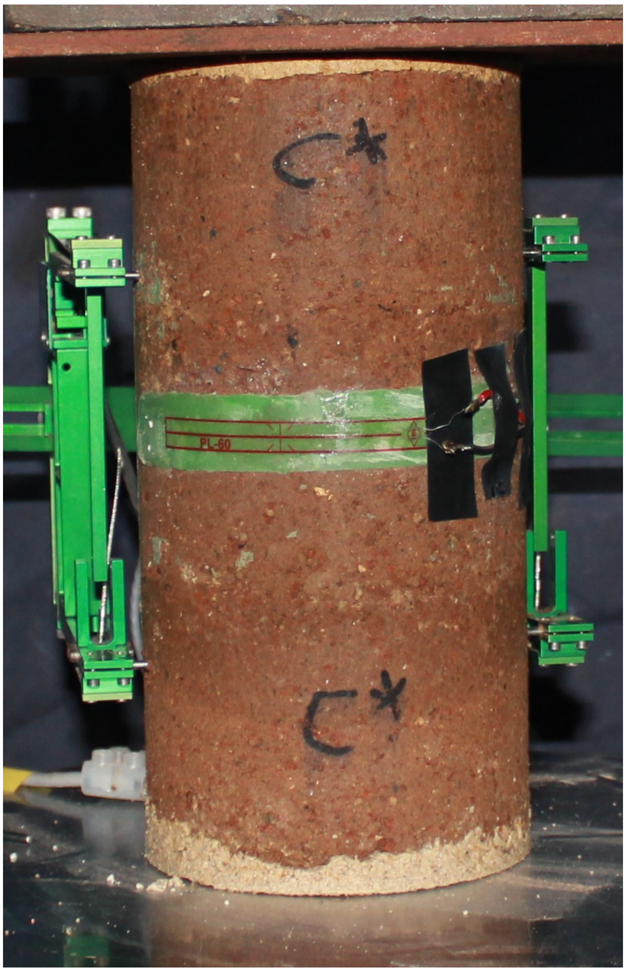


Figure 5. Rammed earth cylinder test

A minimum of three compressed blocks were tested in uniaxial compression for each series. The blocks were only tested wet following 48 hours complete immersion in water. The frogs were filled with a 1:3 cement : river sand, mixture and plywood plates were placed between the block and platen. The blocks were tested under load control, in a uniaxial testing machine, at a rate of 0.15 $N/mm^2/s$ to failure. As with the rammed earth cylinders the compressed earth blocks were tested in two phases: series 1 tested at the Indian Institute of Science, India after either 3 days (72 hours) of heat curing and air dried for 28 days (alkali-activated) or 28 days curing (cement &

lime); and series 2 between 200 and 230 days after compaction at the University of Bath, UK.

For each block series four stacked bonded prisms were prepared for compression testing. Prisms were only tested at 28 days from construction, and were submerged in water for 48 hrs before testing. Each test was carried out at a displacement rate of 6 μm/s. Extensometers, having a gauge length of 100 mm, were used to measure the longitudinal strain of the specimens under loading.

3.4 Thermal tests

The thermal conductivity and Specific Heat Capacity was determined for three rammed earth cylinders and the four compressed earth block series. The tests were conducted at the University of Bath, when the specimens were between 200 and 230 days old. Prior to testing the specimens were conditioned for 1 month by storing under constant temperature (23 ^{o}C) and Relative Humidity (50%). The thermal properties of the blocks was measured width-wise (across 110 mm), mirroring likely direction of heat flow in a wall. In contrast the rammed earth cylinders were tested lengthwise, to accommodate the sensor flat surface. However, the direction of heat flow is perpendicular to that normally expected in a rammed earth wall.

The thermal properties were measured using ISOMET 2114, a transient plane source device, and using a surface probe IPS 1105. It applies a dynamic measurement method, which enables user to reduce the measurement time in comparison with steady state measurement methods. This method's validity for small samples has been previously verified [24]. Measures of thermal conductivity, λ

(W/mK), thermal and volume heat capacity (J/m^3K) were obtained. The volume heat capacity was converted to specific heat capacity (J/(kg.K)).

3.5 Life Cycle Analysis

Because of a lack of local Life Cycle Analysis (LCA) data, the EcoInvent database was used to determine the Global Warming Potential (GWP) of the different masonry systems. While a comprehensive LCA would include other impact categories (particularly abiotic depletion and waste disposal when assessing the difference between mined aggregates and waste materials), these are not included here because of the lack of reliable broader LCA data for the different waste materials.

In the analysis only the material contribution is presented as the contribution of the manufacturing process is very difficult to assess in the Bengaluru region. This is because the manufacture and construction of earth based masonry systems in Bengaluru often uses labour intensive methods, and these are seldom adequately addressed in LCA software [25]. In the case where firing of bricks was required, local values were used [26] as this was the major GWP component in these systems. Where heat curing of the alkali-activated materials was required, the GWP was calculated by assuming the materials required heating from an ambient temperature of 30 °C and the CO_2-eq was 0.167g CO_2-eq/°C per kg material. This was calculated by taking the typical firing temperature [27] and CO_2-eq emissions from manufacture of fired clay bricks in the informal sector in India [26] and extrapolating for different curing temperatures.

GWP values for mined sand were used for the CDW, GS and PBGS aggregates as there was insufficient data to make any other assumption. The values for FA and GGBS were taken from Habert et al [28], assuming an economic allocation of impacts to these industrial by-products.

4. Experimental results

4.1 Rammed earth compression tests

The compressive characteristics, together with dry density and water absorption, for the full-size rammed earth cylinders are presented in Table 5. The results for each series are for three replicate cylinders. Series 1 specimens were tested following either 72 hours curing and air dried in laboratory for 28 days (alkali-activated) or 28 days curing (cement & lime). Series 2 were tested at between 220 and 228 days after ramming. The 28 day tests were completed in India, with the later tests undertaken in the UK.

Table 5. Rammed earth test results (see below)

The dry densities for the rammed earth cylinders were consistent across the six series, averaging around 1885 – 1915 kg/m^3, with no particular correlation with either binder type, aggregate type or age. Water absorption values varied in a relatively narrow range (10.7 – 15.1%) are more varied but with no particular correlation to mix ingredients. The mix with CDW showed marginally higher water absorption (~12%) than the one with PGBS (~11%). However, water absorption values were higher for the specimens tested in the UK (Series 2); this is likely to be attributed to small variations in test methodology rather than any significant material differences.

Only wet compressive strengths were measured for the full-scale rammed earth cylinders. The cement & lime stabilised cylinders average wet compressive strengths varied between 2.7 and 4.1 N/mm^2 after 28 days. The alkali-activated cylinders were consistently stronger than the cement and lime cylinders, achieving wet strengths after 31 days between 5.6 and 11.9 N/mm^2. Tests were repeated at between 212 and 223 days, with wet strengths of both the cement & lime and alkali-activated series increasing on average by 11%. The improvement in strength for cement & lime can be attributed to continued pozzolanic reactions and carbonation of the binders. Strength enhancement for the alkali-activated cylinders can be attributed to the continuation of the geopolymerisation reactions, as well as potential carbonation of any calcium hydroxide present in the FA or PBGS. The cylinders using the PGBS aggregate achieved highest strengths for both binder types, whilst the MS consistently produced the weakest rammed earth. The compressive strengths for all series are suitable for loadbearing rammed earth construction [29].

The stress-strain characteristics of the rammed earth cylinders were also measured during Series 1 tests. The stress strain curves for the cement & lime and alkali-activated materials are presented separately in Figures 6 and 7 respectively. Interestingly, although the alkali-activated cylinders were between 109% and 194% stronger, the average initial tangent moduli for the alkali-activated materials, compared to the cement stabilised specimens, were between 9% and 59% lower, Table 5. Peak strains, around 0.002, were similar for all series, irrespective of binder, except noticeably the alkali-activated series using MS aggregates.

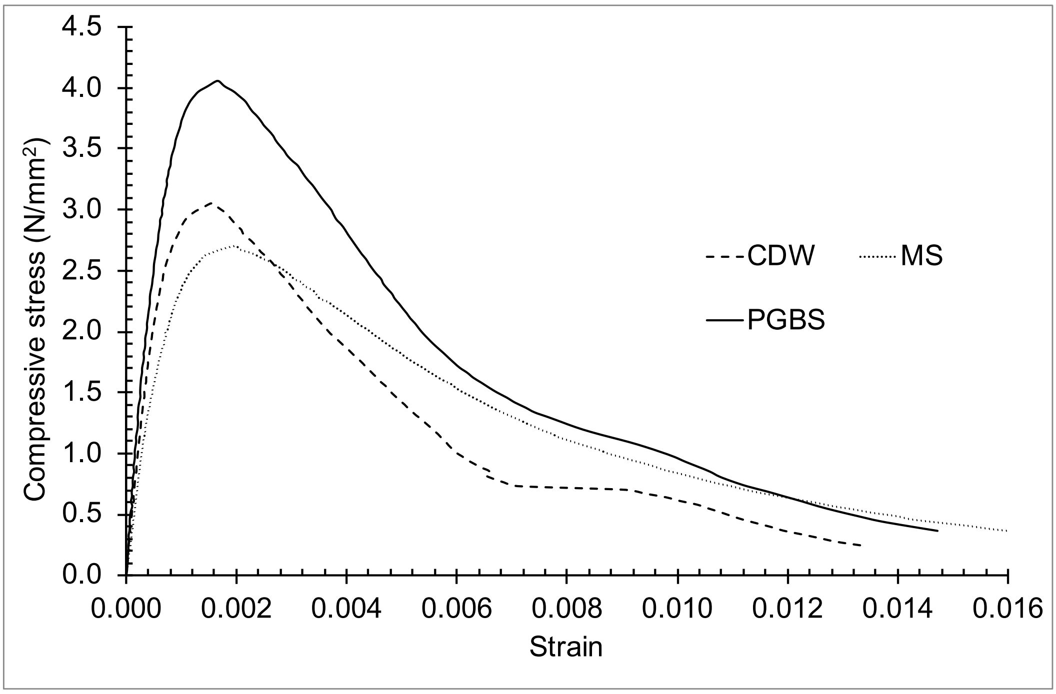


Figure 6. Stress-strain curves for cement & lime stabilised rammed earth cylinders

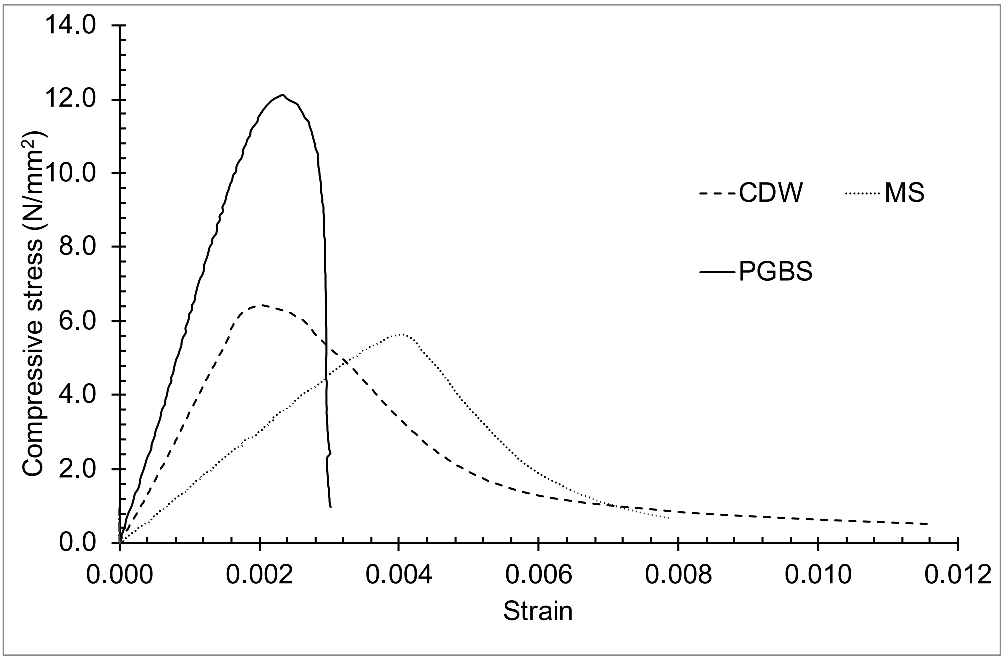


Figure 7. Stress-strain curves for alkali-activated rammed earth cylinders

4.2 Compressed Earth Block compression tests

The wet compressive strengths of the compressed earth blocks are presented in Table 6, together with dry densities and water absorption values. The results for each series are for three or four blocks. The initial Series 1 tests were completed in India, with the later tests undertaken in the UK.

Table 6. Compressed earth block test results

Solid waste	Series I					Series II					
	Dry Density (kg/m^3)		Water absorption	Wet compressive strength (N/mm^2)		Dry Density (kg/m^3)		Water absorption	Wet compressive strength (N/mm^2)		Age (days)
	Mean[1]	C.V.		Mean[1]	C.V.	Mean[2]	C.V.		Mean[2]	C.V.	
	7% cement + 2% lime stabilised (28 days old)					7% cement + 2% lime stabilised (212-228 days old)					
CDW	1940	0.0%	13.9%	6.7	3.7%	1985	0.5%	13.1%	9.1	4.9%	228
MS	1950	0.0%	12.1%	7.8	8.5%	1970	0.2%	12.2%	9.3	2.5%	228
PGBS	1880	0.0%	14.2%	8.9	5.7%	1970	0.0%	12.3%	11.6	5.9%	228
	12M NaOH + 15% FA (31 days old)					12M NaOH + 15% FA (200-215 days old)					
CDW	1955	0.0%	12.3%	15.0	7.4%	2000	0.2%	11.9%	19.1	2.9%	202
MS	1985	0.0%	10.9%	17.0	17.4%	2000	0.3%	10.7%	24.0	3.3%	203
PGBS	1945	0.0%	11.1%	21.9	3.4%	2010	0.1%	10.5%	27.9	3.1%	200

[1] Average of three tests
[2] Average of four tests

For compression testing the frogs were filled with rich cement-sand mortar. The dry densities presented are net values, with allowance made for frogs when determining net volume of each block. The dry densities vary between 1880 and 2010 kg/m^3; except for one apparent anomaly the densities recorded were consistent across the six series, irrespective of aggregates and binder. However, in contrast with previous tests reported here the water absorption values show marked difference between the cement & lime blocks and alkali-activated blocks. The water absorption for the cement & lime blocks were similar to the rammed earth results, whilst the alkali-activated blocks have lower water absorption values: 10.5 - 12.3%.

The wet compressive strengths in the Series I and II tests are reported in Table 6. The strengths are consistently higher than the rammed earth cylinders using identical soil and aggregate materials. However, it must be noted that the aspect ratio of the blocks is much lower than the cylinders, and hence the apparent strength have also been enhanced by this geometrical effect. The initial (Series I) wet compressive strengths for the blocks meet minimum requirements for loadbearing masonry construction. As with the rammed earth materials the alkali-activated blocks are consistently stronger than the cement & lime materials. Also, again the highest strength performance was attained by the PGBS materials, but the lowest strengths were recorded by the CDW rather than the MS as before. Tests were repeated at between 200 and 228 days, with the wet strengths of both the cement & lime blocks increasing on average by 28%, and the alkali activated series increasing on average by 32%.

4.3 Masonry prism compression tests

The results of the masonry prims compression tests, using both cement & lime and alkali-activated blocks with a cement : lime : river sand mortar, are presented in Table 7. The average compressive strengths of the masonry prisms range between 4.76 and 11.5 N/mm^2, values suitable for a wide range of loadbearing wall applications. As the mortar strength was consistent in all prisms the variation in strength, and stiffness, can be primarily attributed to the variation in block compressive properties. The relative strengths of the prism match the same order as for the equivalent blocks (Table 6). Consequently the alkali-activated block masonry is consistently stronger than the cement & lime blockwork: between 53% and 71% stronger for blocks using the same aggregate materials (compared to between 118% and 146% for the blocks). In BS EN 1996: 2005 [30] the function (equation 3.1) to predict characteristic compressive strength of masonry (f_k) is dependent on the normalised unit strength (f_b) to power 0.7. The improvements in measured masonry compressive strength here are compatible with this power relationship using the normalised measured block strengths.

The stress-strain responses of the masonry prisms are presented in Figures 8 and 9. All six series present similar, and expected, responses: an initial steep and linear rise in stress with increasing compressive strain, followed by non-linear phase with decreasing stiffness, and following a distinct peak stress, a ‘falling branch’ reduction in stress with further strain, until specimen facture. The average initial tangent Elastic moduli for the cement & lime stabilised prism series were between 1200 and 1400 times higher than the corresponding compressive strength values. This is a quite typical relationship for cement mortared masonry with standard sized (10 mm) joints [30]. In contrast the average initial tangent Elastic moduli for the alkali-activated masonry prisms were between 560 and 1040 times the average compressive strengths; with exception of the PGBS series around half that for the cement & lime prisms. This observation is in line with that reported above for the rammed earth cylinders, where the alkali-activated materials exhibited comparatively lower stiffness.

Table 7. Masonry prism test results

Solid waste	Wet compressive strength (N/mm^2)		Initial Tangent Modulus (N/mm^2)		Strain at maximum stress	
	Mean	C.V.	Mean	C.V.	Mean	C.V.
7% cement + 2% lime stabilised						
CDW	4.76	7.7%	6700	42.2%	0.0016	33.0%
MS	5.62	6.4%	7300	43.7%	0.0026	58.7%
PGBS	6.92	9.4%	8100	18.0%	0.0029	45.4%
12M NaOH + 15% FA						
CDW	8.15	12.6%	5000	25.9%	0.0023	29.9%
MS	8.61	12.7%	4900	58.5%	0.0037	42.0%
PGBS	11.5	14.4%	12000	23.0%	0.0020	26.4%

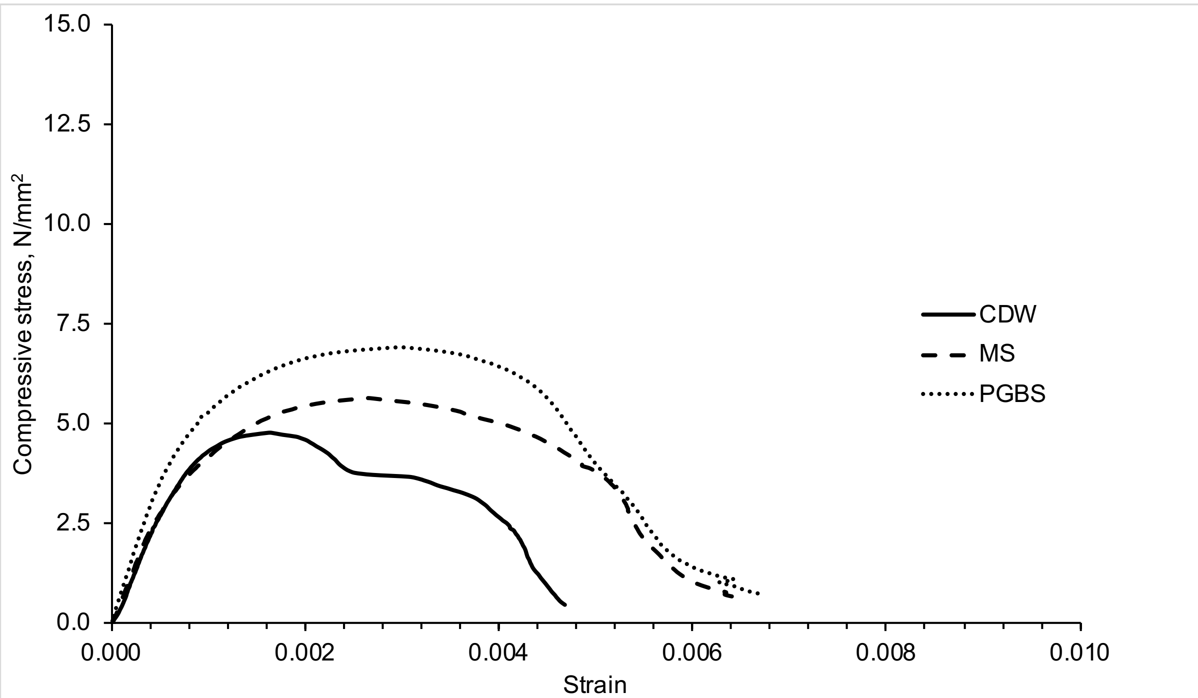


Figure 8. Stress-strain curves cement & lime block masonry prisms

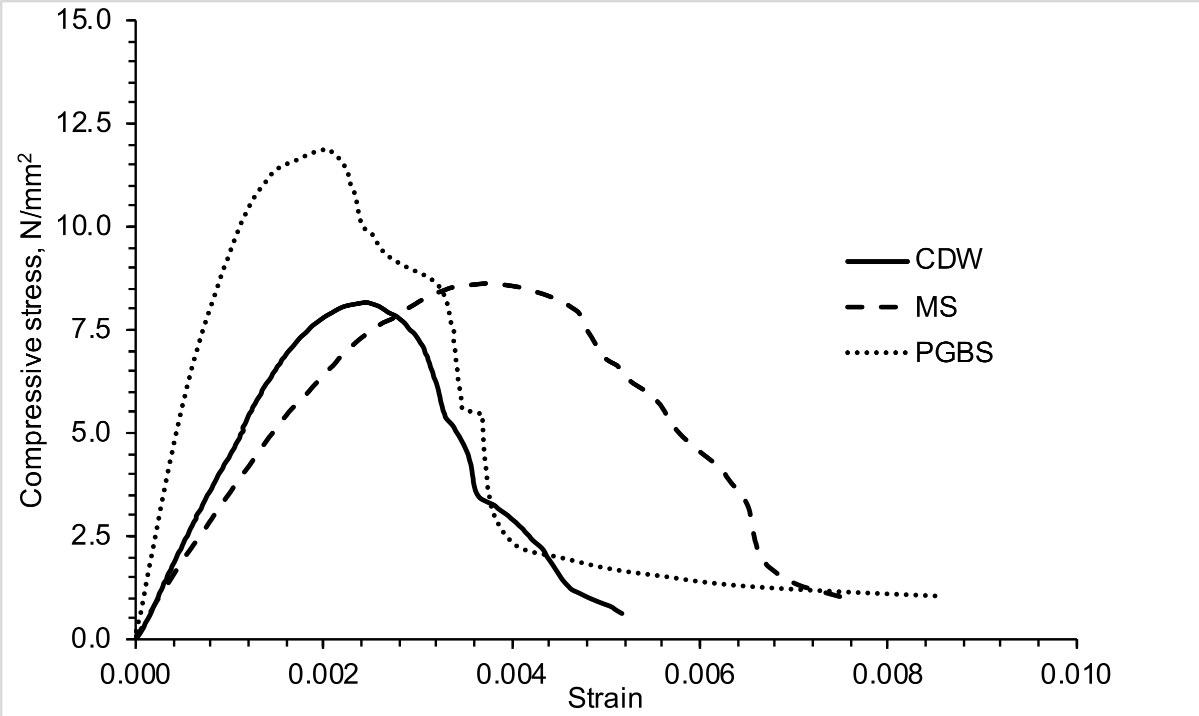


Figure 9. Stress-strain curves alkali-activated block masonry prisms

4.4 Thermal tests

The thermal conductivity and specific heat capacity results for the compressed earth blocks and rammed earth cylinders, measured when the materials had reached between 200-228 days old, are summarised in Table 8. The specific heat capacity values varied between 683 – 766 J/kgK across the six test series, with little correlation with either binder type, aggregate usage or method of construction.

Table 8. Thermal property test results

Solid waste	Thermal Conductivity (W/m.K)		Specific Heat Capacity (J/kgK)		Dry Density (kg/m^3)	
	Mean	CoV.	Mean	CoV.	Mean	CoV.
Compressed Earth Blocks: 7% cement + 2% lime						
CDW	1.11	5.4%	733	6.9%	1985	0.5%
MS	1.13	9.1%	752	5.3%	1970	0.2%
PGBS	0.74	10.5%	755	0.2%	1970	0.0%
Compressed Earth Blocks: 12M NaOH + 15% FA						
CDW	0.94	2.1%	755	0.7%	2000	0.2%
MS	1.17	3.9%	766	5.3%	2000	0.3%
PGBS	0.94	2.1%	753	3.5%	2010	0.1%
Rammed Earth: 7% cement + 2% lime						
CDW	1.31		755		1890	0.3%
MS	1.14		698		1895	0.1%
PGBS	0.80		727		1900	0.1%
Rammed Earth: 12M NaOH + 15% FA						
CDW	1.38		740		1885	0.1%
MS	1.08		683		1895	0.0%
PGBS	0.89		706		1915	1.1%

Thermal conductivity values varied more than those recorded for specific heat capacity, with some trends with materials and techniques evident. The overall range for thermal conductivity was 0.74 – 1.38 W/mK. Overall the thermal conductivities for the rammed earth cylinders were 9% higher than the compressed earth blocks, despite having densities around 5% lower. It is notable that the two rammed earth cylinders using CDW recorded the highest two thermal conductivities. The most evident influence on thermal conductivity was aggregate type, with the values for all specimens using PGBS on average 27% lower than those recorded for the CDW and MS. This can be attributed to more porous nature of PGBS than other aggregates.

The measured Specific Heat Capacity of the materials was similar, with little difference between materials or forms of construction. Specific heat capacity, along with density and thermal conductivity, is a good indicator for thermal mass of construction. The measured values for specific heat capacity are comparable with values for fired clay masonry units.

5. Life Cycle Analysis

The contribution of the different masonry components towards the overall GWP of the walls is illustrated in Figure 10. As discussed earlier, this only includes the contribution of the materials and curing, and not that of the manufacturing process. The compressed earth blocks and fired bricks have an assumed 230 mm thickness with 10 mm mortar joints, while the rammed earth walls were assumed to be 300 mm thick, a common standard practical thickness for rammed earth walls [29], though stabilised rammed earth loadbearing walls of 230 mm thickness have been built in India.

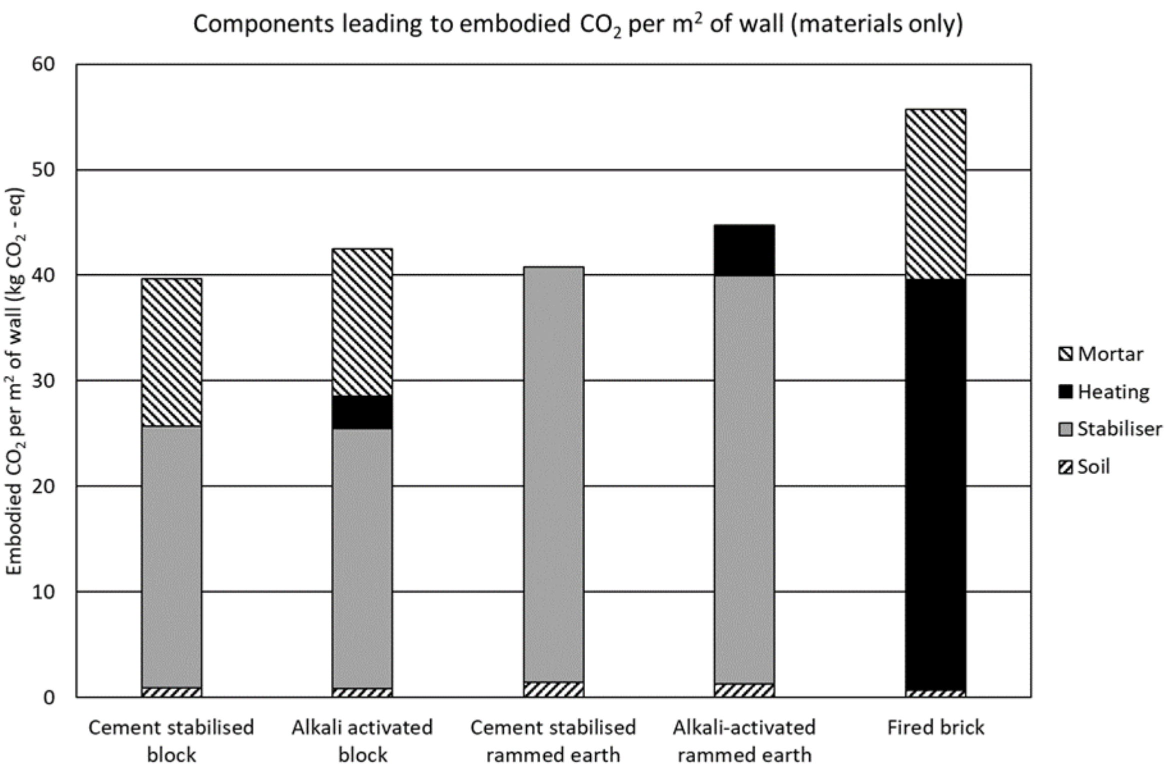


Figure 10. Sources of embodied CO_2-eq in masonry types

As shown, the soil has a minimum contribution to the overall GWP of the wall, with stabilisation (cement, alkali activator / precursor and heating / firing) forming the major contribution. The mortar for the block / brick systems had the second largest effect, but because the walls for these were thinner than for the rammed earth walls, the overall result was a slightly lower GWP per linear metre of wall than the corresponding rammed earth wall. As shown, all the earth block systems have a lower GWP than fired bricks which are commonly used in the Bengaluru area of India.

The effectiveness of the GWP in providing load carrying capacity is illustrated in Figure 11. This was determined by multiplying the masonry wet compressive strength (Table 8) by the assumed wall thickness (again 230 mm for the block or brick and 300mm for the rammed earth) to obtain an indicative load carrying capacity. While this does not provide an accurate estimate of load carrying capacity as it excludes the effect of concentrated loads, buckling, eccentricity, lateral loading and a number of other factors, it does provide a relative measure of performance between the different systems. Data from Gumaste et al. [31] was used for the fired brick masonry strength as this previous research was conducted using different bricks, mortars and bonding patterns used in the Bangalore area of India. Only the data for fired brick masonry with wall thicknesses of approximately 230 mm was used.

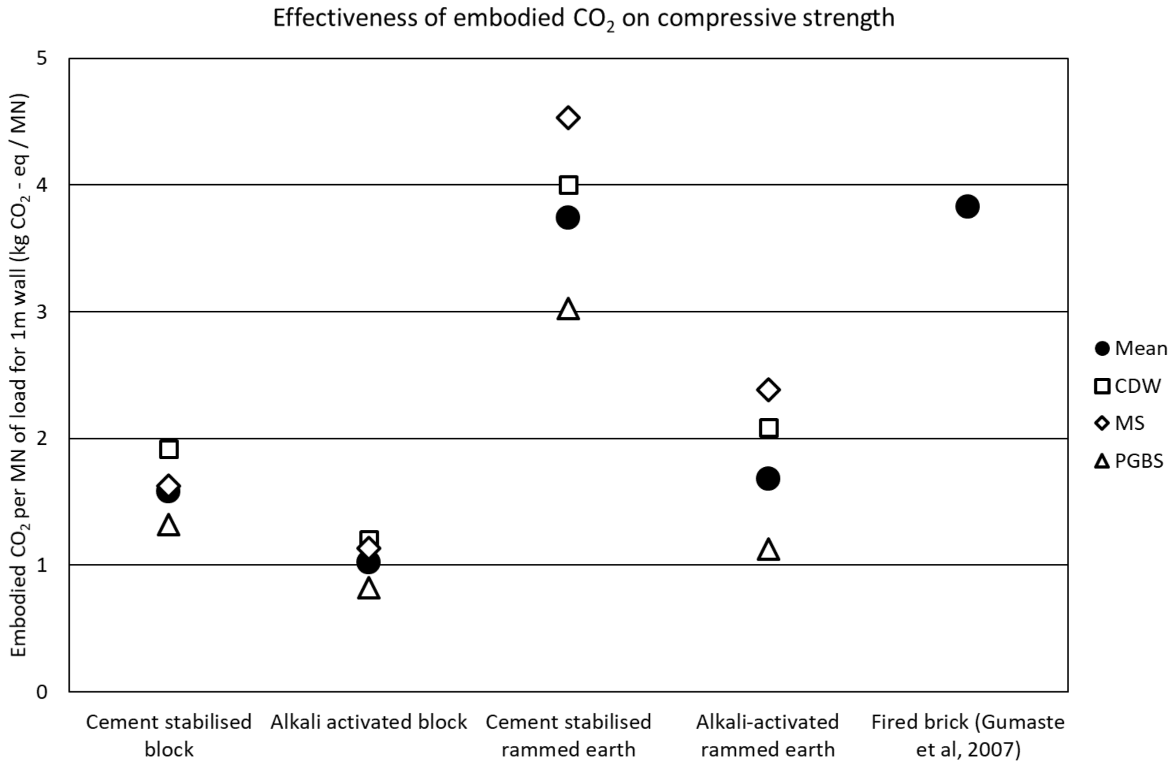


Figure 11. Effectiveness of embodied CO_2-eq on compressive strength

The GWP was divided by the indicative load carrying capacity to determine which system was making most efficient use of the GWP required for manufacture. As shown, the alkali-activated block masonry had the lowest GWP per MN of load carrying capacity, largely because of the comparable GWP to the other earth block systems, but higher strength (Figure 10 and Table 8). The PGBS aggregate mixes had lower GWP than the other aggregate types for the supplied loading. This is because of the higher strength of these mixes but assumed identical GWP between the different aggregates as described earlier. As shown in Figure 10, the soil (comprising the subsoil and aggregate) had a minimal effect on the overall GWP, so it is possible that this is a true reflection of behaviour. This will need confirmation by analysing the actual processing conditions of the different aggregate sources and will also require assumptions on allocation of impacts to both the CDW and PGBS.

6. Practical considerations

Rammed earth and compressed earth block construction are both largely site based activities and require quite high levels of manual labour. The manufacture of blocks can off course be more readily suited to off-site factory manufacture, but in India, for example, in-situ production of blocks using manual presses is more common practice. This approach has many advantages, including maximising the use of on-site soils and reduced transportation. Though rammed earth wall panels can be successfully manufactured off-site the most common approach remains in-situ construction, with freshly mixed materials compacted in successive layers between temporary forms. Both techniques have successfully developed to adopt the use of cement stabilisation. Compared to more traditional unstabilised materials, in-situ cement stabilised materials require the careful storage and handling of cement, correct batching and mixing of materials, and initial moist curing, under wet burlap for example. Cement in itself needs to be handled correctly during mixing in particular, as exposure to cement can led to skin burns and other health problems for example. Guidance for cement stabilised block and rammed earth construction is available, including: Torgal & Jalalim 2011 [32]; Hall et al, 2012 [33]; Krahn, 2018 [34]. However, if alkali-activation is to replace cement as the preferred method of stabilisation solutions to a series of practical issues need to be resolved.

There are safety concerns with using high concentration alkali solutions, particularly in the qualities required for block manufacture, in the informal sector where safety protocols may not be as well developed as they are in larger manufacturing plants. The transportation of solid sodium hydroxide pearls instead of concentrated solutions may be considered to have improved safety, but these require dissolution in water to make the activator solution, and this is an exothermic reaction which can create additional safety problems. This is of particular concern for rammed earth where larger mixes (and therefore alkali quantities) are commonly used and where it is difficult to manufacture the walls in a central plant. It is theoretically possible to mitigate against some of the safety issues by using a combination of sodium carbonate and calcium hydroxide instead of sodium hydroxide. Both have a much lower pH than sodium hydroxide, but will form sodium hydroxide when mixed in the presence of sufficient water (with inert calcium carbonate as a reaction by-product), but this needs to be tested in practice before implementation. It will also increase the GWP of the mixes [35].

The equipment for alkali-activated block and rammed earth production (mixers, presses, formwork, tools) need not differ from that used in cement stabilised works. Items (tools, forms) made from aluminium should of course be avoided. Equipment requires cleaning after use in similar manner.

In keeping with wider concrete technologies, procedures for in-situ cement stabilised materials can be adopted in curing to ensure adequate hydration of binders. Alkali-activated materials rely on thermal curing at 50 – 80 ^{o}C for a few days for geopolymerisation. Heat curing products for around 3-days can much more readily achieved and controlled under factory conditions, where the infrastructure for such curing is likely to be more readily available. In contrast heat curing on site is more problematic, especially on remote sites where regular energy supplies might also be limited. Consequently alkali-activated block off-site factory based production is a feasible option, in-situ curing of rammed earth is arguably not.

Disposal and recycling issues of cured alkali-activated blocks and rammed earth materials expected to be similar to cement stabilised materials. Materials can be crushed and reused as demolition waste in new stabilised earth products for example.

In summary widespread adoption of site manufactured and cured alkali-activated earth products is likely to be limited due to potential problems of curing at elevated temperatures, however, factory produced blocks and other products could provide solutions with lower embodied carbon compared to current solutions.

7. Discussion

As the compressed earth block and rammed earth cylinders have different geometries, the block compressive strengths have been normalised to a standard 2:1 height : width ratio for direct comparison with rammed earth cylinder strengths; Table 9. The block strengths have been geometrically normalised using shape factors in BS EN 772-1:2011 [36]. In applying the shape factor, the average block strengths are reduced by 1.60. Although the discrepancies in strengths reported in Tables 7 and 8 are somewhat reduced, the differences between the material performance remains statistically significant. None of the normalised paired samples of blocks and Rammed Earth (for a given stabilisation method, aggregate type and age) are statistically equivalent according to TOST procedure ($p>0.05$). Furthermore, all the samples, with the exception of Rammed Earth with PGBS stabilised with 12M NaOH + 15% FA and tested at 212 days, are statistically different even after normalisation. This is clearly observed with the cement stabilised rammed earth strengths are between 27% and 45% lower than the equivalent blocks. For the alkali-activated materials the range of strength difference increases to between 13% and 60% reduction for the rammed earth. In part the difference, for identical raw materials and mixes, can primarily attributed to differences in compaction processes. Each distinct layer in the rammed earth cylinders is roughly equivalent to block height, with each layer ‘separated’ by a dry joint. Therefore, a fairer comparison is arguably between the rammed earth strengths and block masonry performance, i.e. the materials as used within a wall construction.

The rammed earth and block masonry characteristic compressive strengths are presented in Table 10, including a further comparison with the experimental masonry strengths and BS EN 1996:2005 [30] predictions (f_k). In comparison the experimental characteristic rammed earth cylinder strengths can be taken directly as representative of wall capacity [37]. It is interesting to note that in five of six series the masonry strengths were higher than the corresponding rammed earth strengths. However, this is a rather limited comparison, and is in contrast with previous work by Venkatarama Reddy and Kumar [38] that reported the compressive strength for rammed earth to be 20-30% higher than that of equivalent CEB masonry. It should be noted that the mortar strength (f_m = 5.3 N/mm^2) was rather high relative to some of the block strengths. The predicted values for characteristic masonry strength are consistently lower compared to the experimental values, though the comparison with the stronger alkali-activated series is a closer match.

Table 9. Normalised mean compressive strengths

Series: 7% cement + 2% lime	**Normalised mean compressive strength (N/mm²)**	
	28 day strength	212-228 day strength
Compressed earth blocks		
CDW	4.20	5.69
MS	4.88	5.82
PGBS	5.56	7.25
Rammed earth		
CDW	3.06	3.50
MS	2.70	3.20
PGBS	4.05	4.10
Series: 12M NaOH + 15% FA	31 day strength	200-215 day strength
Compressed earth blocks		
CDW	9.38	11.9
MS	10.6	15.0
PGBS	13.7	17.4
Rammed earth		
CDW	6.43	6.90
MS	5.63	6.00
PGBS	11.9	14.2

Table 10. Characteristic compressive strength values (N/mm^2)

Series: 7% cement + 2% lime	Expt. rammed earth cylinders[1]	Expt. CEB masonry prisms[2]	Predicted f_k (BS EN 1996: 2005)
CDW	1.49	3.85	2.88
MS	2.39	4.73	3.21
PGBS	3.86	5.32	3.50
Series: 12M NaOH + 15% FA	Expt. rammed earth cylinders[3]	Expt. CEB masonry prisms[2]	Predicted f_k (BS EN 1996: 2005)
CDW	5.30	5.62	5.06
MS	3.34	5.93	5.54
PGBS	10.4	7.42	6.60

[1] Derived from 28 day test values
[2] Derived from 28 day prism test values
[3] Derived from 31 day test values

The addition of PGBS, rather than CDW and MS, produced consistently the highest strengths across the rammed earth and blocks irrespective of binder type. Although the PGBS shows some slight pozzolanicity (Table 3), and therefore explain better performance for both binder types compared to the MS samples, the CDW showed similar pozzolanicity to the PGBS yet also developed lower strengths. The differences in chemical compositions (Table 2), in particular the relatively higher calcium content in the PGBS, together with the slightly coarser grading of the PGBS (Figure 1), may have also contributed to its better performance, but the full benefits of using PGBS is still subject to on-going work.

Comparing compressive strengths of materials containing CDW and the MS, the overall picture indicates that inclusion of CDW has had no significant deleterious effect on performance. For blocks using CDW the strengths are down by up to 20% (average 13%) compared to materials using MS; MS materials here can be considered the base-line performance. In contrast rammed earth strengths are improved by 9-15% compared to the base-line by using the CDW. Although for comparison with past work CDW cannot clearly be considered a standard consistent material, the results reported here are broadly supported by the work of Jayasinghe et al. [18].

When like-for-like aggregates have been used the alkali-activated blocks and rammed earth consistently out-perform the equivalent cement stabilised specimens in mechanical testing. This of course does not lead directly to the recommendation for adopting alkali-activated binders in place of cement, as aspects of cost and environmental impact need to be considered too. There is need for further refinement in the alkali-activated stabilisation.

The compressive strength of both the cement and alkali-activated stabilised materials improved with age between initial tests (either 28 or 31 days) and 200-228 days old. The enhancement was significant, up to 41% for one series of the compressed earth blocks. Further strength development for the cement stabilised materials can be attributed to pozzolanic reactions and carbonation of the binders. The process of strength gain for the alkali-activated materials is attributed to the continuation of the geopolymerisation reactions, though potential carbonation of any calcium hydroxide present in the FA or PBGS may have further contributed to this development. Miranda et al [14] reported that strength development of alkali-activated blocks, stored under ambient conditions, continued for around 150 days; compressive strengths increased by around 75% between 28 and 180 days.

Although the alkali-activated rammed earth cylinders achieved higher strength than the equivalent cement stabilised cylinders, interestingly the measured Elastic modulus was noticeably lower. Compressive strength is commonly used as a predictor for Elastic modulus, but it would seem that different empirical relationships may be needed between cement and alkali-activated stabilised materials. Further, as well as greater elastic deformations the lower stiffness may also result in higher creep movements too, though this is still to be investigated.

The thermal conductivity of the PGBS specimens were noticeably lower than for the other two materials, although material densities were similar. This can be attributed to more porous nature of PGBS. Sore et al. (2018) measured lower thermal conductivities (around 0.7 W/mK) than for denser cement stabilised blocks (around 1.2 W/mK). Although these values are broadly similar to those measured in this study, the distinction between cement stabilised and alkali-activated is not as evident.

Dahmen's et al [16] study showed that the GWP of cement stabilised and alkali-activated blocks were similar, and these figures correspond with findings from this study. This study also showed that rammed earth and compressed earth blocks had similar GWP with the mortar in the blocks compensating for the increased thickness in the rammed earth walls.

Comparing GWP alone does not account for the difference in strength between different masonry systems and if this is included, alkali-activated compressed earth block appear most promising. Information on the minimum strength requirements, wall thickness, and whether the GWP of these alkali-activated masonry systems can be reduced while reducing the strength or thickness needs to be determined. As the bulk of the GWP in the walls can be attributed to the stabiliser (either cement or alkali-activated), reducing stabiliser content is likely to result in a GWP reduction.

8. Conclusions

This paper has presented novel findings comparing mechanical and thermal performance of stabilised earth products using either cement or alkali-activation. The following conclusions may be derived from the work presented:

- Products using PGBS produced consistently the highest strengths across the rammed earth and blocks irrespective of binder type. Elements of the PGBS are thought to remain active for cement and lime stabilisation, and add further precursor material for alkali-activation.

- The use of CDW has had no significant deleterious effect on mechanical performance.
- In five of six series the masonry strengths were higher than the equivalent rammed earth material strengths, indicating perhaps that masonry may be structurally more efficient than rammed earth. However, this is in contrast to earlier studies and warrants further study.
- Compressive strengths of compressed earth block and rammed earth materials meet current standard requirements for loadbearing construction.
- In these specific tests the alkali-activated blocks and rammed earth consistently out-perform the equivalent cement stabilised specimens in mechanical testing. Further refinement in the alkali-activated stabilisation process is needed.
- In contrast to compressive strength, the measured elastic modulus of the alkali-activated materials was noticeably lower than the equivalent cement stabilised materials. As well as greater elastic deformations the lower stiffness could potentially suggest higher creep movements, though this is yet to be evaluated.
- The thermal conductivity of specimens using PGBS were noticeably lower than for the other two aggregates.
- Rammed earth and compressed earth blocks had similar GWP. However, if difference in strength is considered the alkali-activated compressed earth blocks appear most promising.
- Information on the minimum strength requirements, wall thickness, and whether the GWP of these alkali-activated masonry systems can be reduced while reducing the strength or thickness remains to be determined.

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List of Figures

Table 5. Rammed earth test results

	Series 1											Series 2					
	Dry Density (kg/m^3)		Water absorption	Wet compressive strength (N/mm^2)		Initial tangent modulus (N/mm^2)		Strain at peak stress		Age at testing		Dry Density (kg/m^3)		Water absorption	Wet compressive strength (N/mm^2)		Age at testing
	Mean	C.V.		Mean	C.V.	Mean	C.V.	Mean	C.V.			Mean	C.V.		Mean	C.V.	
7% cement + 2% lime stabilised																	
CDW	1900	0.0%	12.7%	3.06	16.3%	5040	33.6%	0.0015	26.0%	28 d		1890	0.3%	15.1%	3.50	6.6%	222 d
MS	1905	0.0%	12.0%	2.70	3.7%	3707	24.6%	0.0017	19.0%	28 d		1895	0.1%	12.9%	3.20	11.5%	223 d
PGBS	1915	0.0%	11.0%	4.05	1.5%	6452	25.5%	0.0016	20.2%	28 d		1900	0.1%	14.1%	4.10	6.4%	221 d
12M NaOH + 15% FA stabilised																	
CDW	1890	0.0%	12,3%	6.43	5.6%	3412	21.1%	0.0020	14.1%	3 d		1885	0.1%	13.3%	6.90	6.2%	214 d
MS	1900	0.0%	11.4%	5.63	12.9%	1563	27.9%	0.0040	14.3%	3 d		1895	0.0%	14.6%	6.00	5.0%	215 d
PGBS	1915	0.0%	10.7%	11.92	4.1%	5876	3.8%	0.0023	2.0%	3 d		1915	1.1%	13.8%	14.20	11.7%	212 d